4WGP 105-12-1

4TH WEATHER GROUP PAMPHLET

WEATHER

VARIATION OF STRONG WIND SPEEDS WITH HEIGHT FROM 30 TO 500 FEET

15 FEBRUARY 1962

UNITED STATES AIR FORCE

FOREWORD

The variation of ~~low~~ level wind speeds with height is of particular interest to meteorologists supporting operations concerned with missile and aircraft tests of guidance, control and safety factors, structural problems, and problems involving dilution and diffusion of aerosols. This study, although aimed at a solution to a particular problem, will be useful to meteorologists supporting a wide variety of Air Force operations. The reader is encouraged to provide this headquarters with criticisms or suggestions for improving the report.

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HEADQUARTERS, 4TH WEATHER GROUP
AIR WEATHER SERVICE (MATS)
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Weather

VARIATION OF STRONG WIND SPEEDS WITH HEIGHT FROM 30 TO 500 FEET

PURPOSE: To present a study of vertical wind data obtained from various locations in an effort to solve the problem of strong wind variability with height at Patrick AFB, Florida.

CONTENTS — Paragraph

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CHAPTER 1

INTRODUCTION

1. The immediate problem to be studied was the variation with height of hurricane winds at the Patrick AFB missile launching sites, but the following discussion is applicable, with certain limitations, to severe tropical and extratropical cyclones generally. The relationships do not appear to vary with wind speed, and thermal stability need not be considered in the case of strong winds. However, surface roughness apparently causes such large variations that the change of wind speed with height at a given location must remain in considerable doubt until actual data become available for that location. Suitable data are not available for Patrick at the present time. Data have been collected for two hurricanes which passed near Brookhaven, L. I., but these are not directly applicable at Patrick because of the differences in roughness of the terrain and the location of the two areas with respect to the ocean. The Brookhaven data, and results obtained at various other locations under non-hurricane conditions, are outlined in this report for the purpose of shedding some light on the problem, but these do not lead to a satisfactory solution.

2. Available data on the vertical ascendent* of low-level wind speeds are not extensive, but the results of investigations conducted under various conditions are consistent in certain important respects. The investigations which have the most direct bearing on the subject at hand are summarized in references 2, 5, 9, 16, and 17. Observations of strong winds have been made from towers 300 to 500 feet high with wind speeds up to 75 mph in extratropical cyclones and up to about 80 mph in hurricanes. In all cases it was found that the increase of wind speed in the vertical could be approximated by a power law. The values of the exponent in the power law (i.e., the rates of increase in wind speed) are fairly consistent at a given site, and even between different sites having similar terrain. It is appropriate to distinguish between the mean, or steady, wind speed as defined by 1-, 5-, or 10-minute averages, and gusts as defined by 1-, 2-, 5-, or 10-second averages, because the gust speed increases with height less rapidly than does the mean speed. Averages of wind speed over different time intervals are not exactly comparable, because the average speed decreases as the period of averaging increases. In evaluating the effect of wind on high structures, it may also be appropriate to consider the dimensions of gusts, because gusts of small size and brief duration affect only a portion of a structure at

*"Ascendent" will be used rather than "gradient" because wind speed increases with height in the lower layers under conditions of strong surface wind.

a time and, for a given wind speed, produce different stresses than large gusts which envelop the entire structure.

3. Most of the investigations have produced mean values of the wind-speed ascendent, averaged over a number of observations at a given site. Only in the case of the Brookhaven data (19) and for gust speeds at Sale, Australia (5) (17) is information available on the variability of the ascendent. Huss, as reported by Gentry (8), has also given extreme values of the gust ratio.

DYNAMIC EFFECTS

4. Lapse Rate. Because of the thorough mixing which takes place in strong winds (i.e., greater than, say 25 mph), the lapse rate normally falls in the neutral range between dry and moist adiabatic. This is true whether the winds are caused by severe tropical or extratropical storms. In hurricanes Carol and Edna in 1954 (19) the temperature difference between the 410- and 30-foot levels ranged from 0.60 to 0.75° C., near moist adiabatic.

5. Wind Speed. Over grassland, the vertical shear has been found to be independent of wind speed over the range 20 mph to 50 mph. In the 2 hurricanes observed at Brookhaven, no change in the ratio of 37-foot wind speed to 150-foot wind speed was found over the range 31 mph to 79 mph at the 150-foot level. However, the mean value of the exponent "p" in the power law (see ~~section~~ Chapter 3) for 13 cyclonic storms of less than hurricane force was found to be 0.25 as compared with 0.28 to 0.31 for 3 storms of hurricane force.

6. Until observations of higher wind speeds become available, it is reasonable to proceed on the assumption that the vertical wind shear for strong wind speeds at low levels is approximately independent of the wind speed itself, or at least that the wind speed effect is small compared with the surface roughness effect.

7. Terrain. Surface roughness and the configuration of terrain are the most important parameters to be considered in attempting to translate results of an investigation from one location to another. It is shown by De Marrais (6) that during unstable conditions at Brookhaven, winds from the southeast, which encounter smoother terrain, yield p in the range 0.09 to 0.12, whereas similar wind speeds from other quadrants yield p in the range 0.13 to 0.23. Tentative models of the wind speed profile have been obtained for "over water", "off-water" (water-to-land), and "off-land" (over land, or land-to-water), including grasslands and woodland. In the case of strong winds the effect of increasing surface roughness is to increase the wind shear over the first few hundred feet in the vertical.

Chapter 3

EXPONENTIAL LAW

8. Investigators have found that the vertical wind ascendent may be fairly well approximated by the exponential law

$$(1) \quad \frac{V_z}{V_o} = \left(\frac{Z}{Z_o}\right)^p$$

where V is the wind speed, Z the height, and p is a constant whose mean value has been determined empirically for various locations. The subscript "o" denotes a reference level, usually 33 feet, representing "surface" anemometer height. Mean values of p determined by various investigators, and the simple ratio of the wind speed at the 1,000-meter and 100-meter height to the speed at 10-meter height, are shown in Table 1. Values at lines a,b,c, and i are derived from observations taken over gently rolling grassland, values at lines d and h over gently rolling terrain with bushes and small trees, lines e,f, and g over gently rolling ground with groves of trees about 10 meters high, and line l over water. Sheppard (16) has collected triple theodolite data on low level winds in the eastern North Atlantic. The experiment was conducted during the passage of a series of rapidly moving cyclones. From these data, 30 cases were selected in which the wind speed in the surface layer was 20 knots or more. The mean value of p between the 20-meter and 50-meter levels was 0.04 with standard deviation 0.14, and between the 20-meter and 100-meter levels 0.03 with standard deviation 0.19. In about half the cases, the wind speed at 20-meters was equal to or greater than the wind speed at 50- and 100-meters. The disturbing feature of the above results is the high variability of the vertical wind shear in what could be regarded as a fairly homogeneous set of observations. Again referring to Table 1, the Brookhaven data are for 1-minute averages of wind speed and all others for 5- or 10-minute averages, except lines j and k which are for gusts. The Brookhaven data are for wind speeds up to about 80 mph at the 37-foot level, whereas the remainder of the data are for wind speeds about 20 to 50 mph. Assuming that effects of stability and wind speed are small, there is a marked increase of p with increasing surface roughness. A question remains whether the Brookhaven data are comparable because of the period of averaging. We propose that they are approximately comparable, because at high wind speeds a 1-minute wind represents dimensions more characteristic of a steady wind than of a gust over the layer within a few hundred feet of the surface. Values of p at lines h and i are remarkably similar, considering the large variation of p for mean wind speeds, and the difference in dimensions of 2-second and 10-second gusts. This strongly suggests that the vertical profile of gust speed may be less dependent on surface roughness than is the profile of mean speeds.

Table 1. Ratios of Wind Speeds at 10-, 100- and 1,000-meter Levels* and Values of p in $\bar{V}_z/\bar{V}_o=(Z/Z_o)^p$

Station	$\bar{V}_{100}/\bar{V}_{10}$	$\bar{V}_{1,000}/\bar{V}_{10}$	p
a. Sale, Victoria, Australia	1.44	1.88	0.16
b. Cardington, Bedfordshire, England	1.48	1.96	0.17
c. Leafield, Oxfordshire, England	1.48	1.96	0.17
d. Quickborn, Germany	1.71	2.42	0.23
e. Brookhaven extratropical storm (75 mph)	1.83	2.66	0.28
f. Hurricane Carol	2.05**	---	0.31
g. Hurricane Edna	2.19**	---	0.29
h. Akron, Ohio	1.66	2.32	0.22
i. Sherlock's data	1.39	1.78	0.14
j. Sherlock, 10-second gusts	(1.20)	---	0.08
k. Brookhaven, 2-second gusts	---	---	0.11
l. Eastern North Atlantic	1.05	---	0.03

*From E. L. Deacon (5); also see (19) and (1).
**Approximate; p on same line not derived from these values.

9. Figure 1 shows various empirical and theoretical representations of the variation of wind speed with height up to 1,000 meters. Note the logarithmic vertical scale. The empirical data are for conditions of adiabatic lapse rate or high wind speeds. Portions of the curves lying between approximately 500 feet (maximum tower height) and 1,000 meters are extrapolated on the assumption that the profile follows the semilogarithmic scale, which is a fair approximation. Curves A, B, C, D, and E are for winds over land. There is some question of the validity of curve E, since it gives impossible values at low levels and is inconsistent with values given in Table 1. (Actual mean values for the Brookhaven hurricanes are shown in Figures 2 and 3.)

10. Curve C for off-land wind is drawn so that the 40-foot wind is 76% of the over-water wind at that level, according to the relationship developed in (20). Curve F is based on Petterssen's estimate that the wind at 10 meters over open water is 70% of the gradient wind. Curve G for off-water wind is drawn so that the speed at the height of 40 feet is 89% of the over-water speed at this height, the ratio obtained in the Lake Okeechobee studies (20). This curve yields $p = 0.12$ between the levels $Z_o = 10$ meters and $Z = 100$ meters. The vertical ascendents depicted by curves C, F, and G are theoretical and, as nearly as can be determined, are not supported by tower data. The ratio between wind speeds at any two levels may be obtained directly by taking the ratio of the abscissas corresponding to those levels.

11. Figures 2 and 3 show the variation of (apparently) 1-minute averages of wind speed with height for 2 hurricanes which passed near the Brookhaven tower. The vertical ascendent approximates a straight line on the semilogarithmic scale.

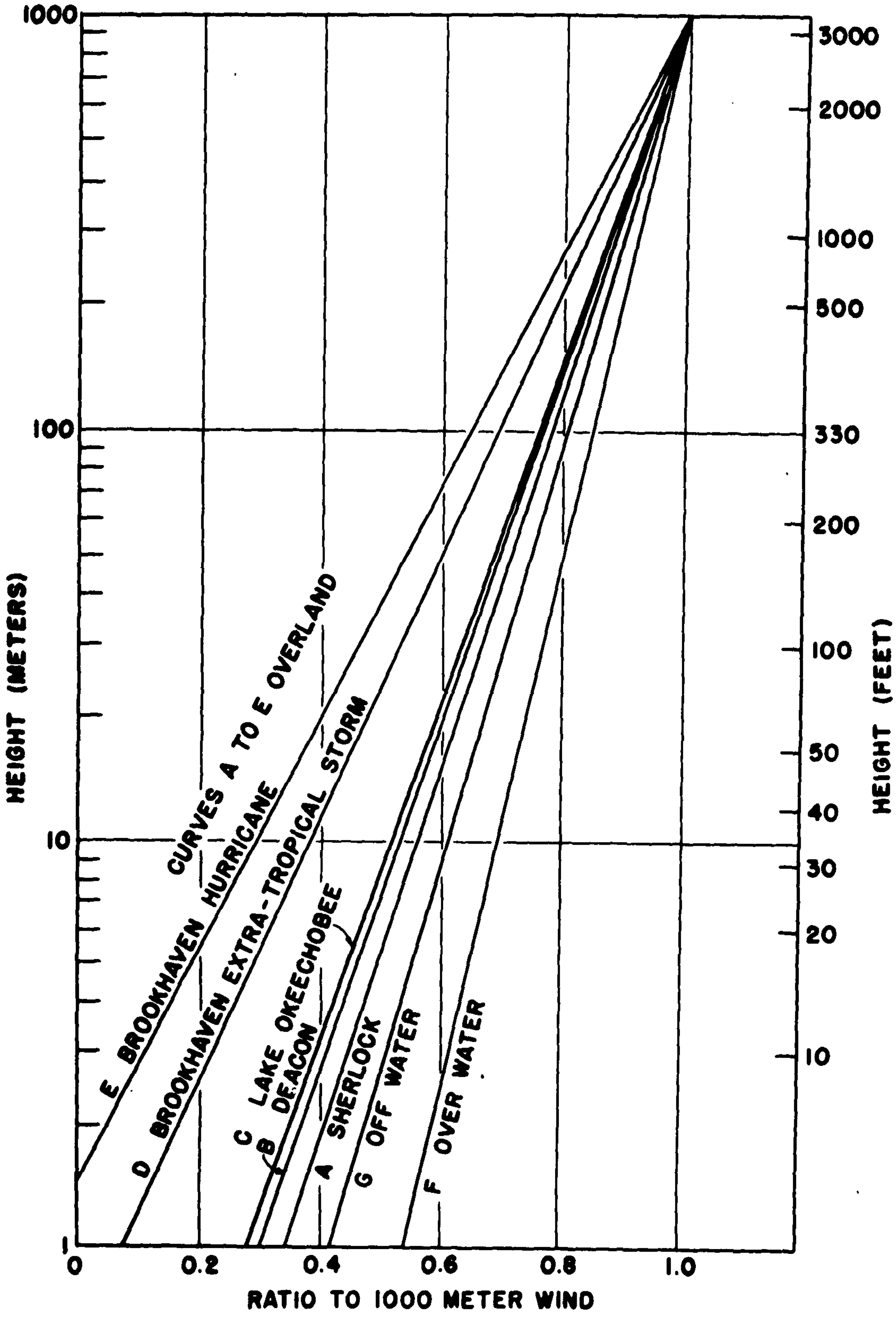

FIGURE I. VARIATION OF WIND SPEED WITH HEIGHT AND OVER VARIOUS FRICTIONAL SURFACES.

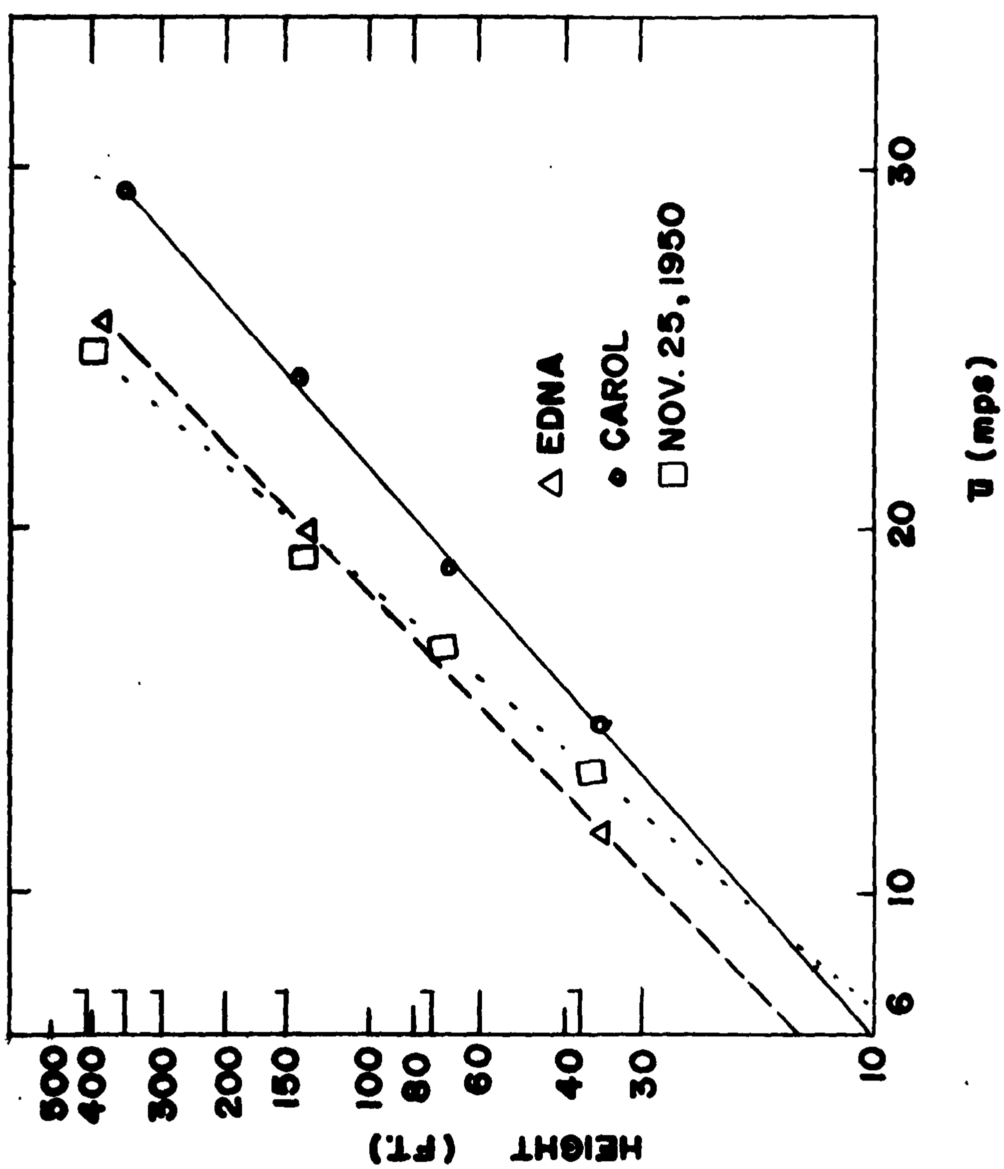

FIG-2 VARIATION OF MEAN WIND SPEED (ū) WITH HEIGHT

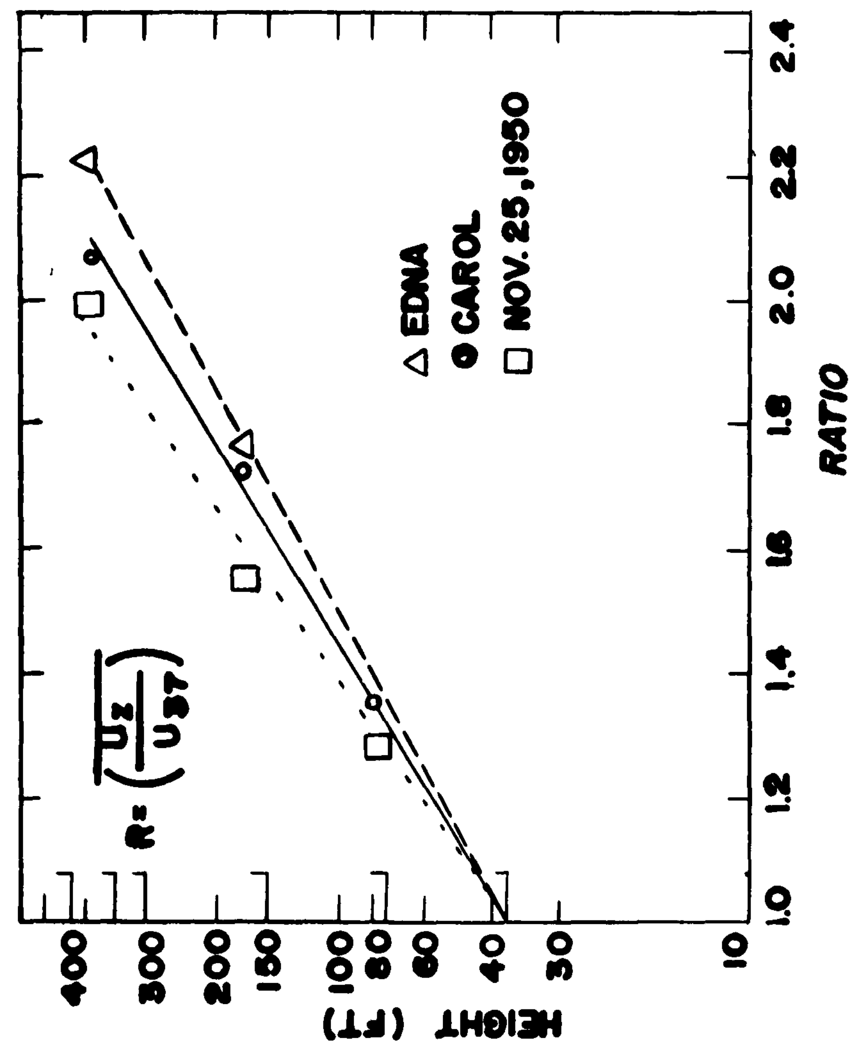

FIG. 3 - RATIOS OF UPPER LEVEL TO 37' LEVEL MEAN WINDS

Chapter 4

GUST PROFILES

12. In general the increase of gust maxima with height is less rapid than the increase of mean wind speed. However, a discussion of gusts is more meaningful if some definition can be made of the dimensions of gusts of various duration. According to Deacon (5), correlation between the 210-foot wind and the 40-foot wind at lag "t" seconds reaches a maximum of 0.05 at about 5 seconds, but similar correlation between the 503- and 40-foot levels was not significantly different from zero. Apparently the 5-second gusts were large enough to envelop the vertical span between the 210- and 40-foot levels but not the 503- to 40-foot span. Sherlock (17) has concluded that gusts of shorter duration than 10 seconds are unlikely to envelop an entire structure 200 feet high. Panofsky and Deland (14) have proposed a model for the structure of low-level turbulence in which the smallest gusts are approximately circular, while larger ones are elongated parallel to the wind. If it is assumed that a 1-second gust belongs to the circular variety, such a gust having a speed of 60 mph would have a vertical extent of 88 feet. Extending this reasoning to 2-second gusts and higher wind speeds it seems to follow that a strong 2-second gust could envelop most of a 200 foot structure. The value of p in the power law was found to be about 0.08 to 0.10 for 10-second gusts over grassland and 0.11 for 2-second gusts at Brookhaven.

13. Table 2 gives the ratio of gusts to mean speed at various levels over relatively smooth terrain. Investigators agree that the ratio of gusts to mean speed decreases with altitude. However, the mean speed increases with altitude, so that the difference between gust speed and mean speed may not vary much between different levels. This appears to have been the case at Brookhaven. Values obtained for short-period gusts at Lake Okeechobee (20), which are comparable to Table 2, were 1.43 for off-water winds, 1.80 for off-land winds at 30 mph, and 1.59 for off-land winds at 60 mph. Table 3 gives means and standard deviations of the ratio of 2-second gusts and lulls to 1-minute mean speeds for Brookhaven.

14. Figure 4 shows the height variation of gust speeds and mean speed at Sale, Australia, over slightly rolling grassland about 20 miles from the sea. Observations were taken under conditions of dry adiabatic lapse rate and wind speeds 20 to 70 knots at the 40-foot level. Curve A is based on maximum gusts in an average period of 8 minutes irrespective of times of occurrence at various heights. Curve B is the same, but over 2-minute periods. Curve D shows the variation of mean speed with height, averaged over all runs. Curve C gives the height variation, relative to maximum gusts at the 40-foot level, of speeds occurring at the instant when the average speed at the 3 levels, 40, 210, and 503 feet was a maximum.

Table 2. *Ratio of Peak Gusts to Average Wind

Ht. above ground (feet)	Mattice* 20 mph	Mattice* 47 mph	Huss	Sherlock
85	1.50	1.47		
30				1.50
40			1.63	1.47
100			1.42	1.39
160			1.37	1.35
220			1.31	1.32
280			1.30	1.30
350			1.27	1.28

*Average wind and gust are defined as follows:

Mattice	gust	peak of trace
	avg.	fastest single mile
Huss	gust	Maximum 1-second wind
	avg.	average highest 5-minute containing gust
Sherlock	gust	maximum 10-second wind
	avg.	maximum 5-minute average for storm

Table 3. Means and Standard Deviations of the Ratio of 2-Second Peaks and Lulls to 1-Minute Mean Speeds for Brookhaven Hurricanes (19)

Height (ft)	Carol (1954)				Edna (1954)			
	lull/mean		peak/mean		lull/mean		peak/mean	
	M	sd	M	sd	M	sd	M	sd
37	.61	.11	1.43	.14	.59	.11	1.45	.16
75	.67	.08	1.38	.13	---	---	---	---
150	.69	.09	1.28	.09	.70	.08	1.29	.09
355	.76	.07	1.22	.08	---	---	---	---
410	---	---	---	---	.79	.07	1.18	.07

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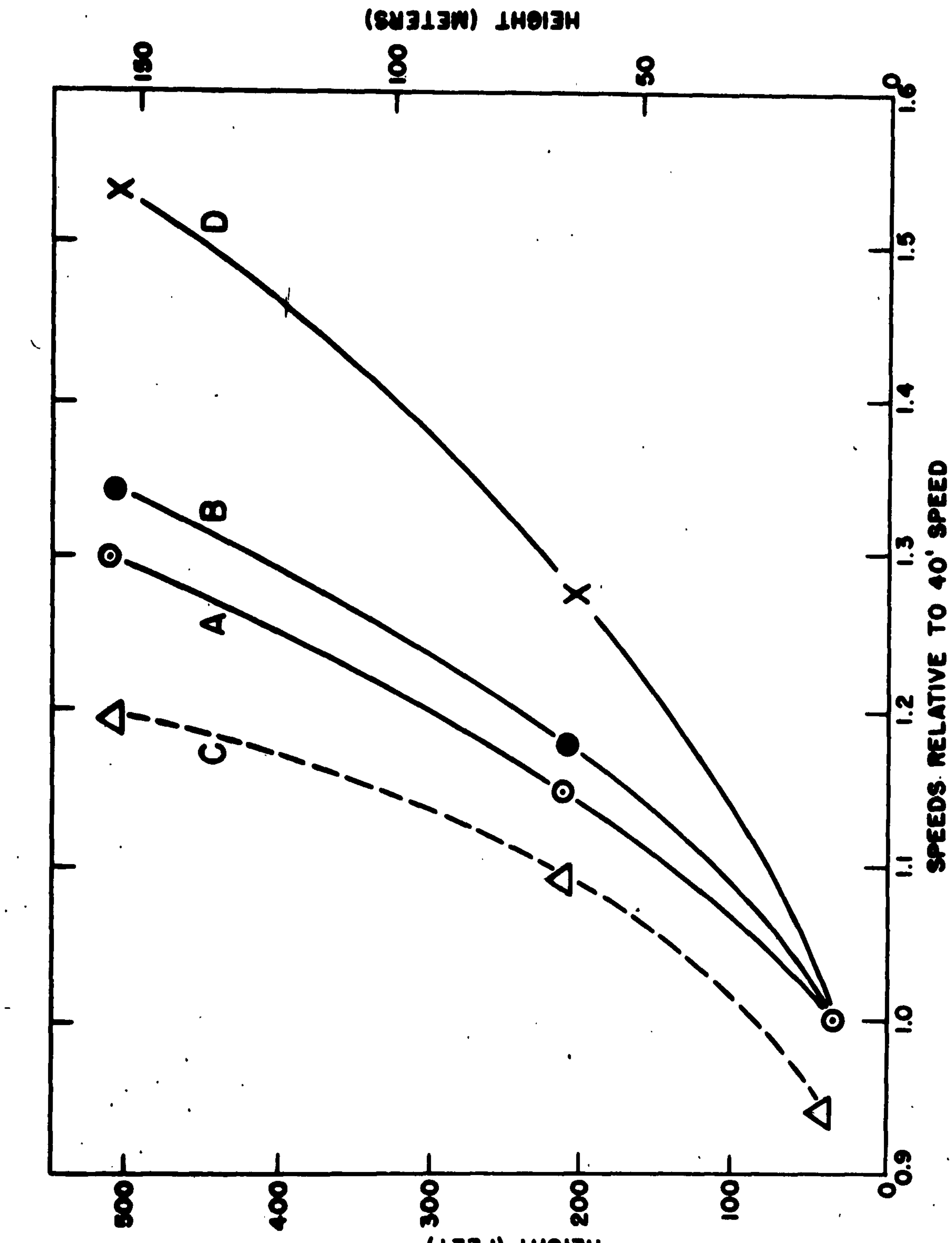

FIGURE 4. HEIGHT VARIATION OF GUST SPEEDS AND OF MEAN WIND SPEED.

It is thus an attempt to represent gusts large enough to affect the entire structure. Curve C is a median curve for gust speeds, which means that in about 50% of cases stronger gusts would be expected. The mean ratio of gusts to mean speed was 1.089, with a standard deviation of 0.055. If at each height the abscissa of curve C is increased by 5%, the resulting curve is likely to be exceeded only 1/6 of the time. As the original observations had an average duration of about 8 minutes, it follows that, in about 1 hour of storm, one large gust may be expected to exceed curve C.

15. Curve 1, Figure 5, shows an additional adjustment of 1% to make it applicable to an anemometer height of 33 feet. The adjustment to curve C is not exact, but more observations including very high wind speeds would be needed to warrant more elaborate treatment. The most important problem concerning these results arises when they must be related to another specific site having its own characteristic terrain. Curve 2, Figure 5 is Sherlock's recommendation (17) for use in design of high structures. Curve 3 is proposed by the American Standards Association. The latter gives too rapid an increase of gusts with height up to 300 feet to be representative of grassland exposures and would be more suitable for rougher terrain.

16. Figures 6 and 7 show the ratio of 2-second gusts to 1-minute averages, and the ratio of the peak of the trace to the 5-minute average containing the peak, respectively, for the Brookhaven hurricanes. Note that, whereas the mean wind speed increases with height along with a straight semilogarithmic curve, the gust ratio (gust/mean) decreases with height along the same type of curve. While the gust speed increased more rapidly with height at Brookhaven than over grassland ($p = 0.11$ as compared to $p = 0.08$ to 0.10), the gust ratio was smaller at low levels at Brookhaven than over grassland, and decreased less rapidly with height.

17. Figure 8 is a compilation of the results of the various investigations discussed above, and shows the large differences between the Brookhaven observations and those taken over smoother terrain. Reference levels are 10 and 100 meters, but the diagram is valid for intermediate levels. The lower reference level was chosen at the usual anemometer height because this is the height at which forecasts of surface wind speeds are verified. Solid lines represent various values of p; those beginning at $V_z/V_o = 1.0$ are for mean wind speed, and those beginning at 1.40, 1.44, and 1.70 are for gust speeds. The 1.44 is for the ratio of 2-second gusts to 1-minute means, and the 1.70 for the ratio of 1-second peaks to 5-minute means at Brookhaven. The curves representing vertical extrapolation of gust values by the power law are inconsistent with the dotted lines, which represent gust ratios at the two levels, taken from figures 6 and 7, the former resulting in gust speeds actually less than the mean wind speed at 100 meters. Apparently, either the gust ratios or the given values of p for gusts are not meant to be interpreted in this way.

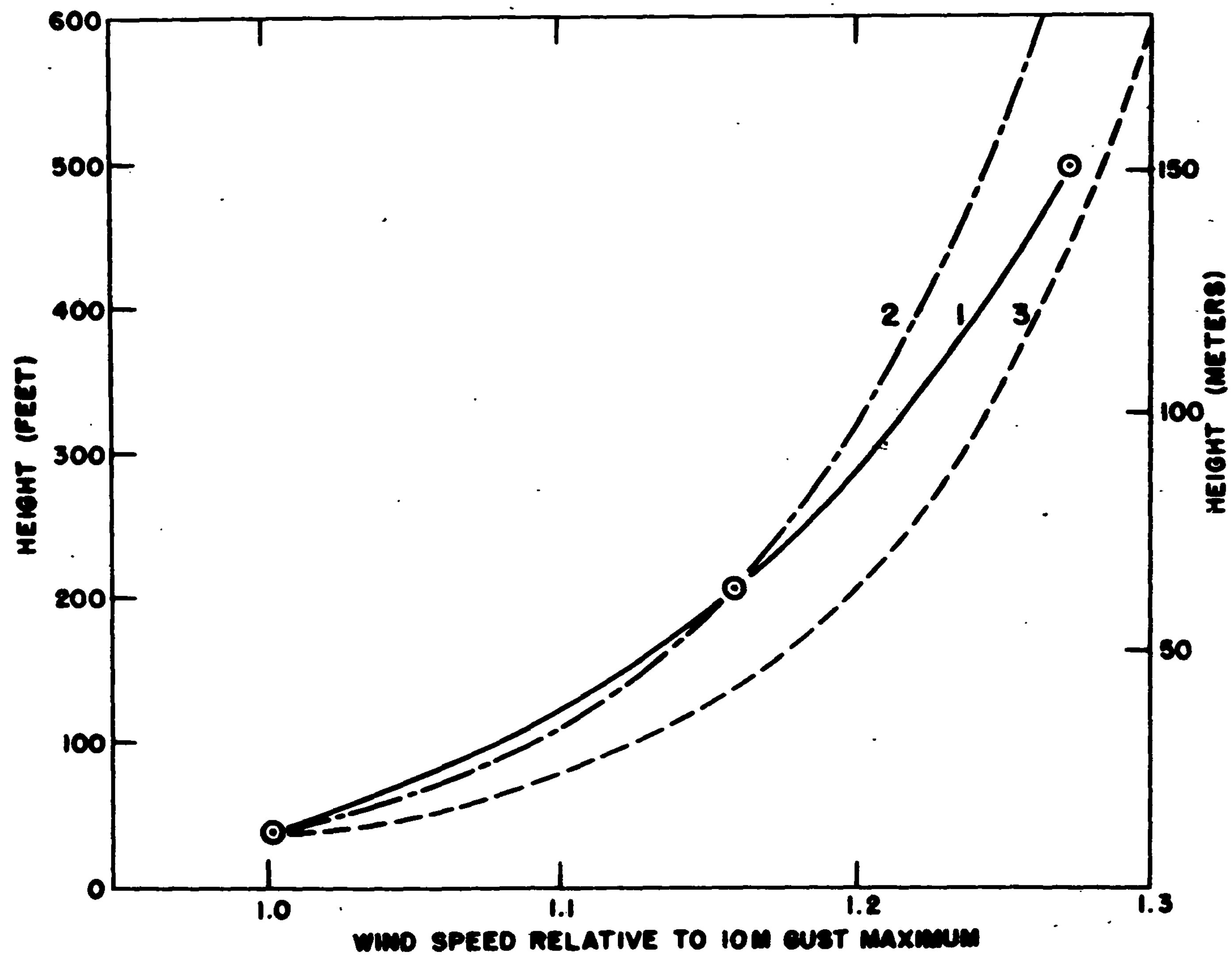

FIGURE 5. COMPARISON OF VARIATIONS OF WIND SPEED WITH HEIGHT RECOMMENDED FOR USE IN THE DESIGN OF HIGH STRUCTURES.

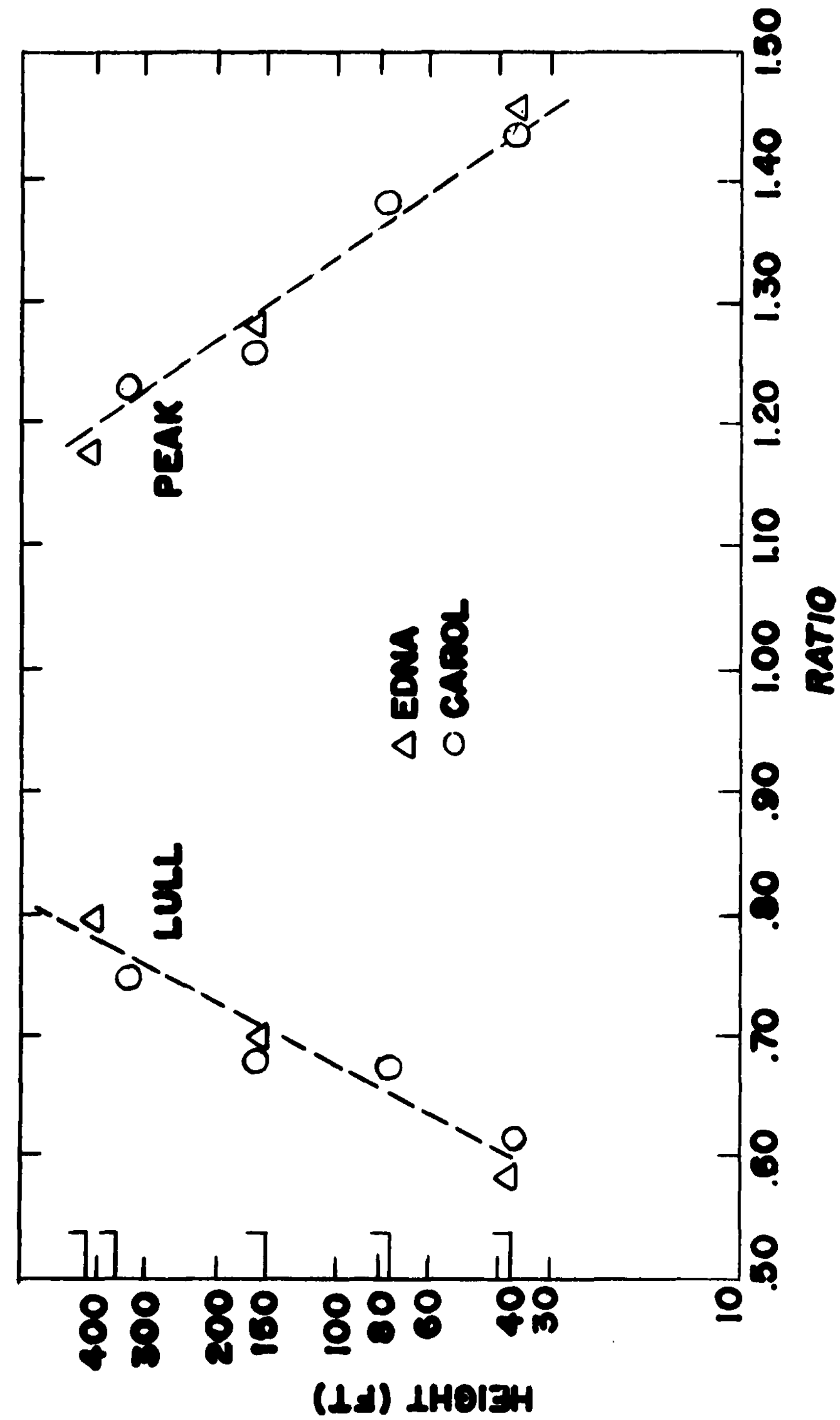

FIG. 6 - RATIO OF 2-SEC. PEAKS AND LULLS TO 1-MIN MEANS

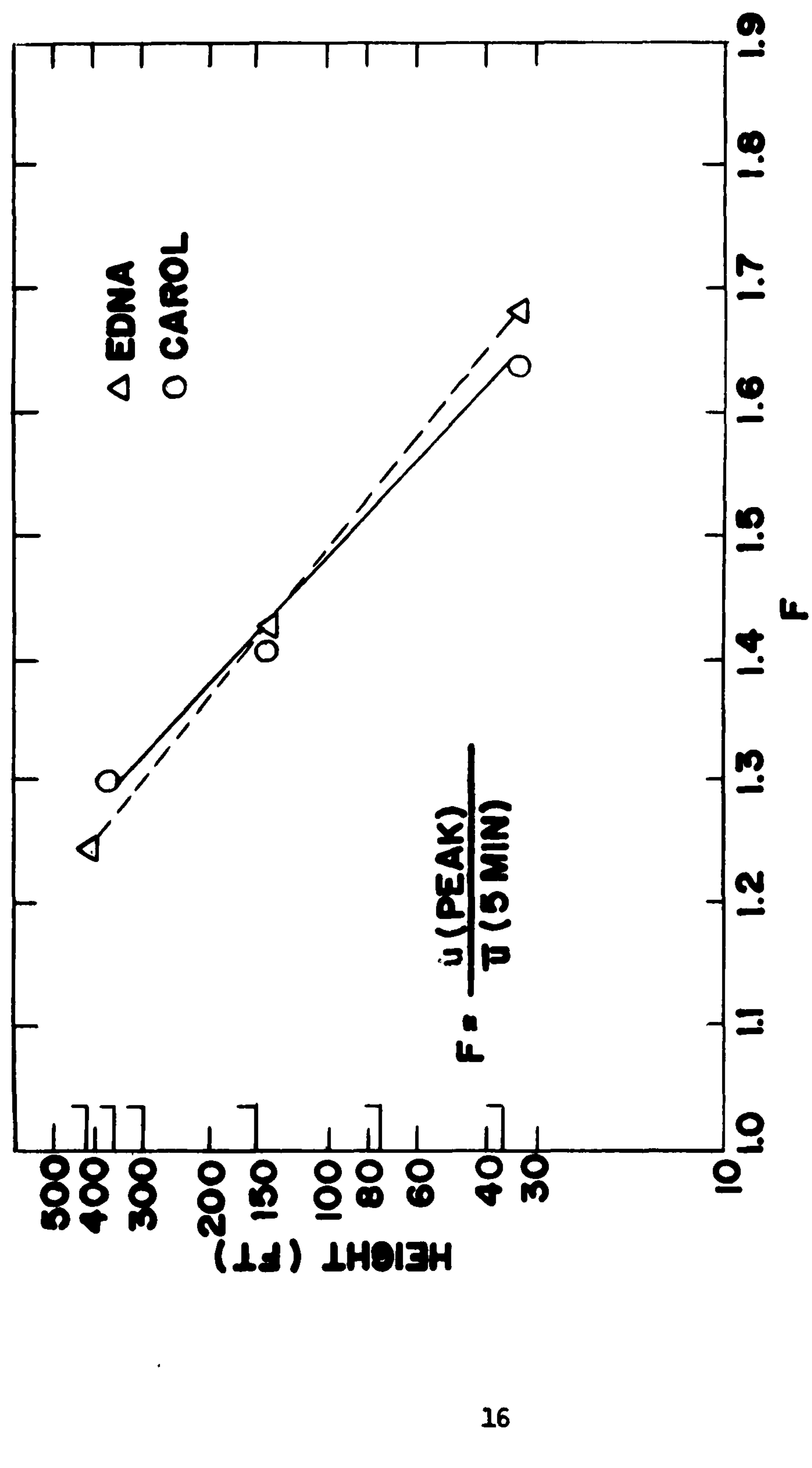

FIG. 7 VARIATION OF GUST FACTORS (F) WITH HEIGHT

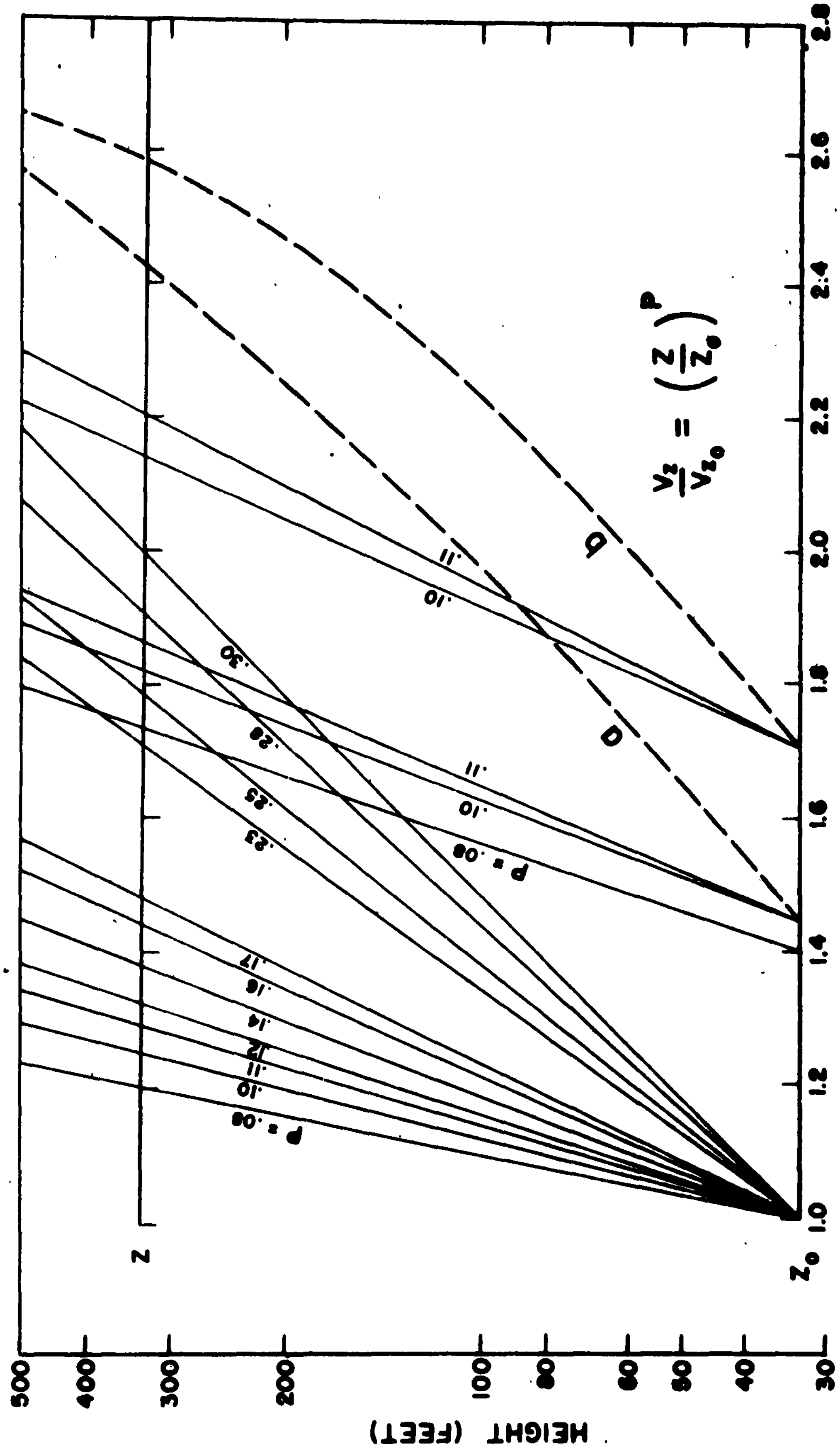

FIGURE 8. COMPARISON OF RESULTS

CHAPTER 5

CONCLUSIONS

18. An authoritative answer to the question of the low-level vertical wind-speed profile in hurricanes for the Patrick AFB missile sites, or any other specific location outside Brookhaven, L. I., cannot be given on the basis of available information. However, in view of the location, the best estimate of mean value of p for 5-minute averages of off-water hurricane winds at the Patrick missile sites is 0.10 and is not likely to exceed 0.14. In cases where the wind direction is from the land, the wind speed will increase more rapidly with height, i.e., p will be larger, because the surface wind speed will be reduced by friction. Table 2 or figures 6 and 7 may be used for guidance in estimating the gust profile, depending on preference for the definition of gusts. The value of p for gusts at Brookhaven was 0.11, only slightly larger than the 0.08 advocated by Sherlock. The best estimate of the mean value of p gusts at Patrick is 0.08; we may estimate with some confidence that the mean value for gusts does not exceed 0.11. Available information does not yield a satisfactory way of estimating the variability of p. However, it appears likely that the variability of p in hurricane situations is considerably less than indicated by Sheppard's data for Atlantic cyclones. This is indicated by estimating the distribution of p which could arise from means and standard deviations of wind speeds at various levels in the Brookhaven data.

19. The spectrum of lateral velocity components can be divided into low-frequency convective and high-frequency mechanical portions. In a hurricane situation the mechanical portion may be presumed to be the most important. Panofsky and Deland (14), in comparing Brookhaven with O'Neil, Nebraska data, have shown that the mechanical portion is sensitive to ground roughness but independent of stability. There is a large diurnal variation in the total spectrum because of the nocturnal minimum of convective activity. The similarity between hurricane and extratropical cyclone data at Brookhaven suggests that the convection produced by condensation in a hurricane does not have a large effect on the vertical profile of wind speed. In any event, it appears that at a given location, vertical relationships obtained from winds in excess of 30 knots in non-hurricane situations should provide a fairly good estimate of vertical relationships in a hurricane. Because surface roughness is apparently the largest single effect, data of this sort are probably more directly applicable than data obtained in a hurricane at another location having much different surface characteristics. Data should probably be collected under nighttime or overcast conditions when the convective component of turbulence is least. Since the vertical profile seems to follow the same power law from 30 feet up to 500 feet, continuously recorded data for any intervening level, such as 100 feet, should prove useful in establishing estimates of the exponent p for a specific location.

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